An Introduction to the Indirect Exposure Assessment Approach: Modeling Human Exposure Using Microenvironmental Measurements and the Recent National Human Activity Pattern Survey

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Indirect exposure approaches offer a feasible and accurate method for estimating population exposures to indoor pollutants, including environmental tobacco smoke (ETS). In an effort to make the indirect exposure assessment approach more accessible to people in the health and risk assessment fields, this paper provides examples using real data from *a*) a week-long personal carbon monoxide monitoring survey conducted by the author; and *b*) the 1992 to 1994 National Human Activity Pattern Survey (NHAPS) for the United States. The indirect approach uses measurements of exposures in specific microenvironments (e.g., homes, bars, offices), validated microenvironmental models (based on the mass balance equation), and human activity pattern data obtained from questionnaires to predict frequency distributions of exposure for entire populations. This approach requires fewer resources than the direct approach to exposure assessment, for which the distribution of monitors to a representative sample of a given population is necessary. In the indirect exposure assessment approach, average microenvironmental concentrations are multiplied by the total time spent in each microenvironment to give total integrated exposure. By assuming that the concentrations encountered in each of 10 location categories are the same for different members of the U.S. population (i.e., the NHAPS respondents), the hypothetical contribution that ETS makes to the average 24-hr respirable suspended particle exposure for Americans working their main job is calculated in this paper to be 18 µg/m^3. This article is an illustrative review and does not contain an actual exposure assessment or model validation. — *Environ Health Perspect* 107(Suppl 2):365–374 (1999). *http://ehpnet1.niehs.nih.gov/docs/1999/Suppl-2/365-374klepeis/abstract.html*

Key words: exposure assessment, exposure modeling, environmental tobacco smoke, carbon monoxide, respirable suspended particles, human activity patterns, the National Human Activity Pattern Survey

The indirect approach to exposure assessment was introduced more than 15 years ago (*1*) and has been used to study exposure to carbon monoxide (CO) (*2,3*), benzene exposure (*4,5*), respirable particle exposure (*6,7*), and, more recently, exposure to toxic compounds found in environmental tobacco smoke (ETS) (*8,9*). Several exposure-modeling computer environments have been developed (*10–12*). However, the indirect approach has not yet gained widespread acceptance, even though accurate exposure assessments are crucial in determining safe levels of environmental pollutants (risk assessment) and in determining environmental factors that contribute to disease (epidemiology).

The indirect approach is a modeling approach that simulates exposures using empirical distributions of exposure in specific microenvironments, output from microenvironmental models, and human activity pattern data. The main advantage of the indirect approach is that it can be used to rapidly and inexpensively calculate estimates of exposure over a wide range of exposure scenarios. Models can be used to determine the sensitivity of exposure levels to quantifiable parameters. For example, a computer program can be easily reconfigured to observe the impact of reducing air exchange rates in workplace buildings around the United States.

In contrast, the direct exposure assessment approach, as exemplified by such studies as the U.S. Environmental Protection Agency (U.S. EPA) TEAM and PTEAM studies (*13–15*), NHEXAS (*16*), and the more recent 16-city survey of ETS exposure (*17*), involves the deployment of a large number of personal or microenvironmental exposure monitors. In the direct approach, different exposure scenarios must be investigated by collecting additional data.

Although both the direct and indirect approaches give frequency distributions of exposure for a given population and its important subgroups (such as the strata of age, gender, race, geographic region, and work status), the indirect approach is typically much less expensive and time consuming. A main disadvantage of the indirect approach compared to the direct approach is that there currently is a research need for its systematic validation. That is, the results of a fully developed indirect exposure assessment must be compared to an independent set of directly measured exposure levels. The data-intensive nature of the indirect approach, including the need for detailed human activity patterns, has made validation difficult (*2*), but the availability of new activity pattern and other exposure-related databases (*16–20*) is encouraging.

This article is intended as an introduction to the indirect exposure assessment approach for those in epidemiology and other health-related fields. It is not intended to be an actual exposure assessment and does not contain a validation of modeling methods. It provides an illustration of the indirect exposure assessment methodology through the use of real pollutant concentration and activity pattern data.

In the next section of this article, I introduce the concept of direct human exposure assessment by describing my week-long personal exposure profile for CO. Such a profile cannot be easily measured directly for a large number of people, but it can be approximated indirectly (i.e., through the indirect exposure assessment approach) by separate consideration of average microenvironmental pollutant concentrations and the time spent being exposed in each microenvironment.

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Abbreviations used: ach, air changes per hour; CO, carbon monoxide; ETS, environmental tobacco smoke; NHAPS, National Human Activity Pattern Survey; ppm, parts per million; RSP, respirable suspended particles; U.S. EPA, U.S. Environmental Protection Agency; µg/m^3, micrograms of air pollutant per cubic meter of air.

Microenvironmental concentrations are determined from either measurements or a validated exposure model (e.g., an indoor air quality model). The time exposed is obtained from responses to questionnaires such as the 24-hr recall diary used in the U.S. EPA-sponsored National Human Activity Pattern Survey (NHAPS) study (*19,21–24*). In "Time Americans Spend Being Exposed," I describe some results from NHAPS, including the time spent by Americans in locations where a smoker was reported to be present. Finally, in "Estimating Human Exposure Indirectly," I give two examples of indirect exposure assessment calculations: *a*) the 24-hr CO exposure concentration received by the author on 16 December 1997 from a variety of sources: and *b*) the estimated 24-hr respirable suspended particles (RSP) exposure concentration received by NHAPS respondents from ETS while working their main job.

Direct Exposure Measurements: Personal and Microenvironmental Monitoring

The most accurate way to determine exposures is to measure them using monitoring devices such as active integrating samplers (air pumped through filters at a fixed flow rate), passive integrating samplers such as treated filters with known theoretical flow rates (*25*), or instruments that can be used to collect real-time data, such as the Langan CO Personal Exposure Measurer (*26*) (Langan Products, Inc., San Francisco, CA) and the TSI Model 8510 piezobalance (TSI, Inc., Minneapolis, MN). The latter two instruments have been used successfully in previous field studies of ETS (*27,28*). Large-scale exposure studies have deployed many samplers (usually integrated over 8 to 24 hr or longer) to characterize ETS exposure (*13,17*). These studies have been able to show significant increases in ETS constituent concentrations in locations (e.g., homes and offices) where there is smoking. However, the long sampling times used in these studies (12–24 hr) prevent us from drawing detailed conclusions for specific microenvironments.

Ideally, exposure measurements are highly resolved in time (on the order of an hour or less) so exposures occurring in different locations and from different sources can be precisely differentiated, and are collected for the same individual over extended time periods (days, weeks, or months) to obtain a complete and connected (autocorrelated) picture of the variation in a person's exposure. For example, I collected my own week-long CO exposure profile (using the Langan CO Personal Exposure Measurer) on a recent trip from the San Francisco Bay area through Las Vegas, Nevada, and Boston, Massachusetts. The profile consists of minute-by-minute CO concentrations matched with the precise times that different locations were entered (Figure 1, Table 1). Notice the substantial variation in CO exposure from day to day and from location to location. Each location is associated with different sources of CO. This database can be used to calculate both the average CO concentration and the time spent in each microenvironment. The microenvironments visited over the 7-day period included a smoky bar (12/12), a smoky casino buffet (12/13), a residence with gas heat (12/15–12/16), a smoky airport lounge (12/16), a home heated with oil (12/16–12/19), and many instances of being inside a vehicle in traffic.

Unfortunately, it would be too expensive and burdensome to collect and analyze real-time measurements for a large group of subjects, especially considering the massive quantity of data produced. For example, if 100 people were equipped with real-time CO personal monitors that stored readings every 5 min, a single day of readings would consist of $12 \times 24 \times 100 = 28,800$ data points. In addition, the subjects would be tracked through up to 15 or more different locations, or microenvironments, over the 24-hr period (e.g., home bedroom, home kitchen, front yard, car, playground, school classroom, bus, etc.).

It is unnecessary, however, to collect all of this information at once from each subject when each exposure segment can be determined separately. Because the most common microenvironments such as homes, schools, offices, bars, and restaurants have similar physical characteristics regardless of their locale (e.g., ventilation systems, furnishings, types of sources), exposure levels in each microenvironment can be studied individually with the full complement of real-time apparatus, and these results can be generalized to other nearly identical microenvironments around the country using validated deterministic models (see discussion below). Microenvironmental exposure levels can also be adapted for new populations from representive surveys (i.e., direct exposure assessments) of a given area (*13–17,29*). Subsequently, data on the time spent in each microenvironment, as determined from a study such as NHAPS, are combined with these microenvironment exposure levels, either from models or representative surveys, to produce a complete exposure profile for each subject.

Example

On a recent trip I took with some colleagues to a San Francisco restaurant/bar where smoking was allowed (this visit is also part of the exposure profile presented in Figure 1 and Table 1), real-time RSP (measured using the TSI piezobalance) and CO concentrations (measured with the Langan Measurer) and counts of numbers of smokers were measured for a period of about 2 hr (Figure 2). The single-room venue had an approximate volume of 800 m^3, and an average of one smoker was observed during the 2-hr time period (6:30 PM to 8:30 PM). After subtracting the average background levels (34 $\mu g/m^3$ for RSP from levels measured just outside the bar and 1.5 ppm for CO from levels measured inside a nearby residence where there was no smoking), the average RSP concentration was 68 $\mu g/m^3$ ($n = 36$; $\sigma = 19$; range = 36–116) and the average CO concentration was 1.75 ppm ($n = 119$; $\sigma = 0.4$; range = 1.5–5). These CO and RSP average concentrations reflect the contribution that cigarettes made to the indoor air quality minus contributions from traffic and other outdoor sources (assuming the contribution from cooking was negligible). Before subtracting the background levels, RSP and CO average concentrations were 102 $\mu g/m^3$ and 3.25 ppm, respectively. Thus, the average RSP and CO concentrations were increased by 3 times and 2.2 times, respectively, because of the cigarette smoking. For a person visiting a similar venue where there was an average of one smoker present for the entire trip (and assuming the pollutants are attributable to the smokers and not cooking or other sources), a comparable increase in average exposure concentration might be expected.

But what about for other venues and/or other conditions? We must be able to extrapolate to situations in which more smokers are present, or to rooms with different physical characteristics (e.g., room volumes or ventilation rates). We could either conduct a series of experiments in different kinds of establishments on a number of different days or we could apply a valid indoor air quality model, which is the more cost-effective solution. For the current example, if there were twice as

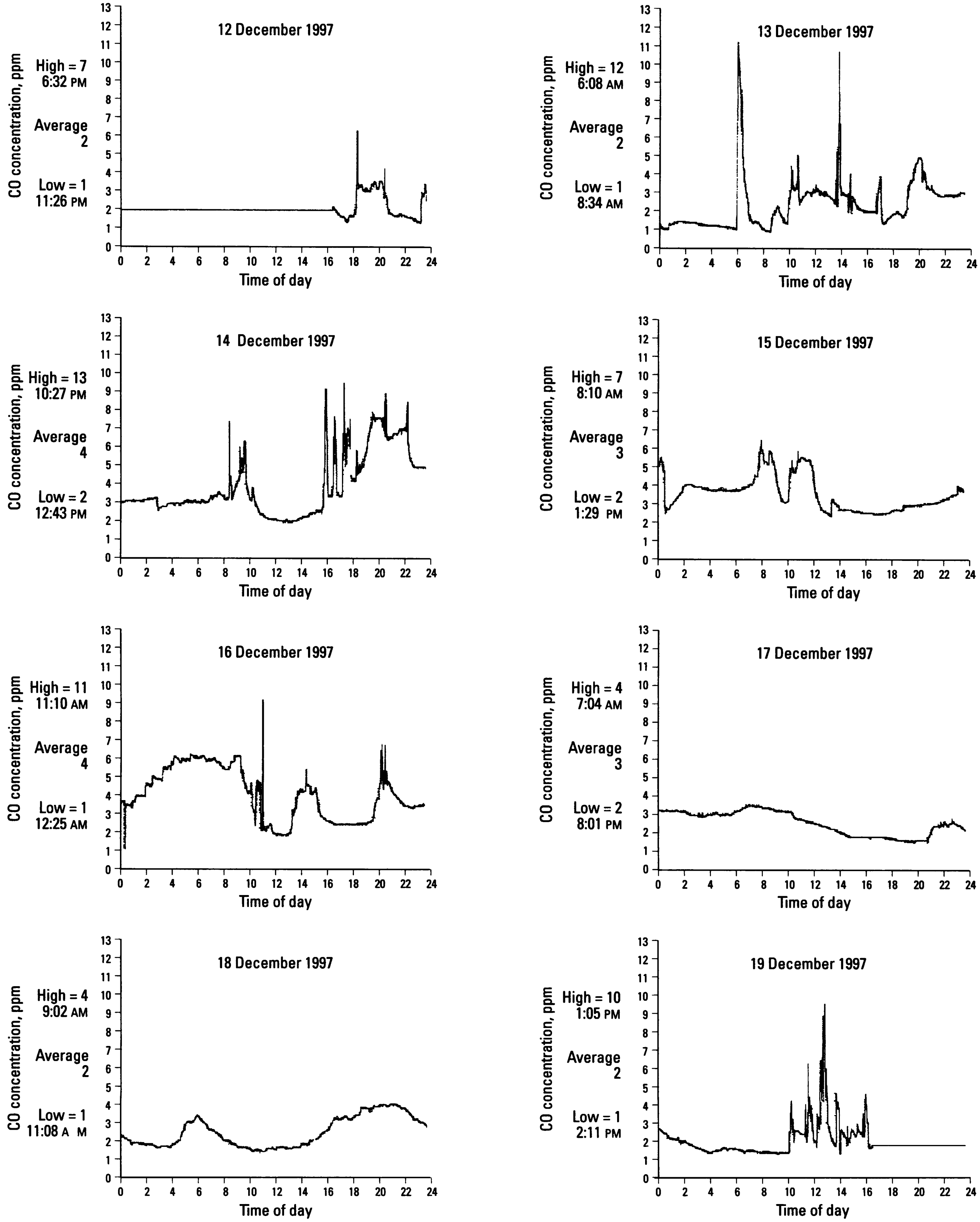

Figure 1. The minute-by-minute carbon monoxide personal exposure profile as measured by the author between 4:30 PM on 12 December 1997 and 4:30 PM on 19 December 1997 using a Langan CO personal monitor.

many smokers on average and everything else remained the same, according to mathematical indoor air quality models based on the mass balance equation the average RSP exposure concentration attributable to smoking would double over the 2-hr time period from about 68 to about 136 $\mu g/m^3$. Halving the room volume or the pollutant removal rate would also result in a doubling of the 2-hr exposure concentration.

Mathematical models that use the mass balance equation have been validated using real-time measurements in taverns (*30*), smoking lounges (*27*), and vehicles (*28*). The article by Ott (*31*) in this volume discusses applications of the mass balance equation in some detail. These models assume that the air in each venue is reasonably well mixed. This is the subject of my article in this volume titled "Validity of the Uniform Mixing Assumption: Determining Human Exposure to Environmental Tobacco Smoke" (*32*).

Time Americans Spend Being Exposed: The National Human Activity Pattern Survey

After exposure concentrations in specific microenvironments, such as the bar/restaurant described previously, have been quantified, the time spent in these microenvironments must be determined before complete exposure profiles can be constructed. The time spent in microenvironments is obtained from human activity pattern surveys. These surveys sometimes rely on recall diaries that ask people to remember the locations they visited for some specified time period (such as the 24-hr period of the previous day). To date, the recent NHAPS study (*19,21–24*) is the most complete survey of the time that Americans have spent exposed to toxic pollutants. Because of its significance to the indirect exposure assessment approach, I have included in this section a description of the main features of the NHAPS.

The NHAPS was carried out from 1992 to 1994 (eight seasonal quarters) for the U.S. EPA by the University of Maryland's Survey Research Center (*22*). A total of 9,386 respondents were interviewed across the 48 contiguous U.S. states about their exposure to air and water contaminants encountered in their daily lives.

NHAPS was patterned after the 1987 to 1990 California Activity Pattern studies of adults and children sponsored by the California Air Resources Board (*33–35*), which collected data on the potential exposure of Californians to common pollutants. These studies (including NHAPS) used a random-digit-dialing methodology to contact potential respondents by telephone. Subsequently, 24-hr recall diaries were collected from respondents to capture minute-by-minute accounts of their daily routines. For

Table 1. Diary of locations visited during the author's week-long CO personal monitoring experiment.

Date	Location	Observed sources	Time entered	Date	Location	Observed sources	Time entered
12/12/97	At a friend's house in San Francisco		4:30 PM		Driving back to house 1		10:12 PM
	At a bar/restaurant in San Francisco	Smokers present	6:25 PM		Arriving at house 1	Candles	10:20 PM
	Back at friend's house		9:00 PM	12/15/97	Driving back to house 2		12:10 AM
	Traveling on the 101N freeway		11:00 PM		Arriving at house 2		12:35 AM
	At home in Berkeley, CA		12:00 AM		Driving to Las Vegas, NV, airport		7:45 AM
12/13/97	Taking a taxi to Oakland, CA, airport		6:00 AM		Arriving at the Las Vegas airport		8:10 AM
	At the Oakland, CA, airport		6:15 AM		Boarding the airplane		8:40 AM
	Boarding the aircraft		7:25 AM		Arriving at Oakland, CA, airport		10:05 AM
	Arriving in Las Vegas, NV		10:00 AM		Riding public transit		10:20 AM
	Driving to a casino		10:15 AM		Walking		11:30 AM
	Entering a casino		10:00 AM		Back at home in Berkeley, CA		–
	Entering the casino buffet	Smokers present	11:10 AM	12/16/97	Driving to Oakland, CA, airport		10:25 AM
	Driving to a store		1:44 PM		Arriving at Oakland, CA, airport		10:50 AM
	At a store		2:04 PM		Boarding airplane		11:20 AM
	Traveling to a friend's house (#1)		2:36 PM		Arriving at Phoenix, AZ, airport		1:09 PM
	At house 1	Incense burning	2:50 PM		In airport cafe/lounge	Smokers present	1:34 PM
	Driving to another friend's house (#2)		–		In main airport area		2:06 PM
	At house 2	Gas heat on	5:20 PM		Boarding airplane		2:45 PM
	Party begins	Some smoking	9:00 PM		Arriving in Boston, MA, airport		7:39 PM
12/14/97	Drive to a casino		8:30 AM		Driving to parent's house		8:15 PM
	Enter casino (diff. from yesterday)		8:40 AM		Arriving at parent's house		8:48 PM
	Enter casino buffet	No visible smokers	–	12/17/97	Remaining at parent's house	Mntrs upstrs	–
	Drive back to house 2		9:34 AM		Remaining at parent's house	Mntrs dnstrs	8:49 PM
	At house 2		9:45 AM	12/18/97	Remaining at parent's house	Mntrs dnstrs	–
	Driving to a store		3:40 PM	12/19/97	Driving to a colleague's office		9:58 AM
	Arriving at store		4:10 PM		Arriving at the office		10:27 AM
	Driving to another house (#3)		–		Driving to Wellesley College dormitory		11:16 AM
	Arriving at house 3	Wood smoke odor	4:48 PM		Arriving at dormitory		11:45 AM
	Inside house 3		4:51 PM		Driving back to parent's house		12:05 PM
	Driving to a store		5:12 PM		Arriving at parent's house		1:02 PM
	In store		5:30 PM		Driving to restaurant		2:31 PM
	Driving to another casino (#3)		5:34 PM		Arriving at restaurant		2:33 PM
	At casino 3	Many smokers	5:54 PM		Driving to copy store		3:50 PM
	Driving to restaurant		6:18 PM		Arriving at copy store		4:12 PM
	Arriving at restaurant	Nonsmoking	6:25 PM		Driving back to parent's house		6:26 PM
	Driving to a bar		8:35 PM		Arriving at parent's house	Mntrs dnstrs	6:45 PM
	Arriving at a bar	A smoker	8:40 PM				

Abbreviations: Mntrs upstrs, monitors placed upstairs; Mntrs dnstrs, monitors placed downstairs. Times are all reported in Pacific standard time (PST).

NHAPS, the diaries were coded into 82 locations (e.g., home, bar, restaurant, office, school), 91 activities (e.g., food preparation, housekeeping, being at work), and whether a smoker was ever present. Thus, these telephone surveys give detailed time-of-day information on where and for how long individuals are exposed to ETS. In addition, both studies queried respondents on specific exposure events (e.g., the number of cigarettes smoked or the type of heat used at home) through a number of follow-up questions. Background information including age, gender, race, education, health, and employment status was collected in the NHAPS study, but data were not collected on specific occupational classifications. This weakness in the NHAPS study limits our ability to conduct detailed characterizations of occupational exposures.

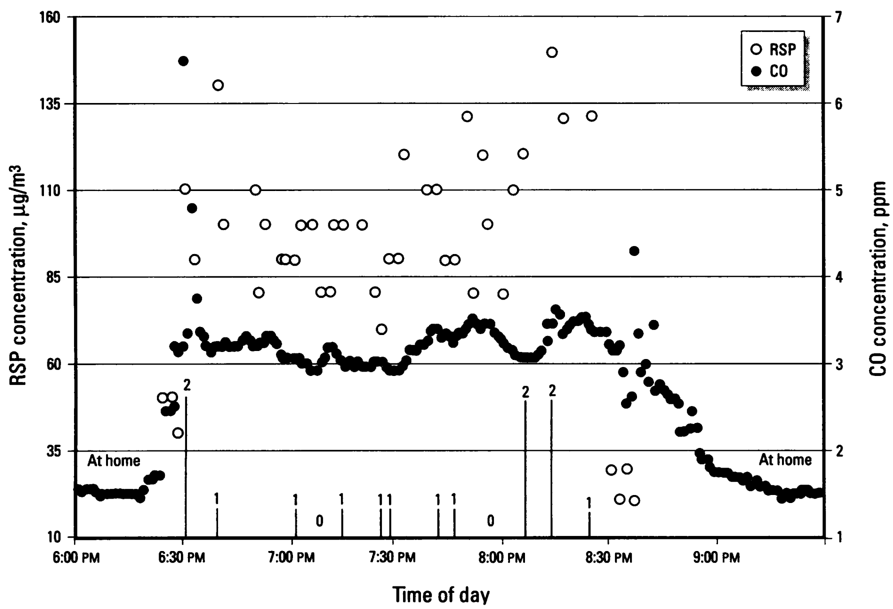

Figure 2. Plot of CO and RSP measured in a smoky bar/restaurant from 6:30 PM to 8:30 PM Friday, 12 December 1997 in San Francisco. The number of smokers present was observed at different times and is indicated by lines and numbers at the bottom of the figure.

Table 2. Background factors and summary of question types for NHAPS questionnaires versions A and B.

Background (grouping) factors	Version A (~50% of respondents)	Version B (~50% of respondents)
Biologic Age, race, gender	Air, storage Gas cans, lawnmower, paints, mothballs, deodorizer, humidifier, windows open, doors open	Air, storage gas, lawnmower, paints, solvents
Status Employment, education Role Children, other adults, work hours, work evening, work outdoors	Air, yesterday Smoking, home/away; others smoke; paints; open flame; glues; solvents; pesticides; floor wax; gas-powered equipment; cleaning agents; excessive dust; stain removers; perfumes; nail polish; gas station; gas stove; microwave; aerosol spray; heating; heavy traffic; roadway; parking garage; walk to car	Air, last 6 months Renovations, paint, floors, addition, carpets, glues, sleep elsewhere, pesticides, vacuum floors, humidifier, gas stove, heat sources Water Shower/bath; dishwashing; washing machine; drinking water, bottle/tap; juices; soft drinks
Geographic Zipcodes, home; zipcodes, work, housing; structure; stories; rooms; carpet; basement; garage	Water Shower/bath, dishwasher, washing machine	Water, last month Pool swimming
Lifestyle Health	Ingestion Children, soil	Ingestion Children, soil; seafood; blackened food
	24-hr diary Activities, locations, smoking, hard breathing	24-hr diary Activities, locations, smoking, hard breathing

Adapted from Robinson and Blair (*22*).

Table 2 contains the general categories of information collected in the NHAPS 24-hr recall diaries and follow-up questions. Approximately half the respondents were given one questionnaire (questionnaire A) and half were given another (questionnaire B) that collected similar general information but focused on different kinds of exposure. The overall NHAPS response rate was about 63%, although it was lower during the first quarter because of difficulties in data collection.

The NHAPS 24-hr recall diary data have no missing values, probably because the respondents were guided by the interviewers to classify every minute of the day into a particular location and activity. In contrast to the 24-hr diaries, the follow-up questions have a substantial amount of missing data, due partly to the dependence of certain questions on a "yes" response to another question. However, much of the missing data seem to have arisen from refusal or inability to answer questions. In addition, follow-up questions were sometimes coded in a mixed-type format containing arbitrary divisions and groupings, making analysis difficult. Thus, the 24-hr diaries appear to be a better source of complete and accurate information on exposure events occurring among the U.S. population even though many follow-up questions are focused on important areas of exposure.

The main drawback of the 24-hr recall diary results is that we are forced to work with the arbitrary categories encoded by the original data collectors. Many of the activity categories appear to be more relevant to sociological issues than to different types of exposure. For example, the original activity codes are divided into general categories of paid work, household work, child care, personal needs/care, education, entertainment/social, recreation, and communication. Unfortunately, there is practically no information on specific types of exposures (except ETS) that occur during, say, housekeeping, food preparation, or being at work. We can identify times when people may be engaged in activities that could involve exposure, but there are few or no categories that pinpoint the precise type of exposure, except the categories of smoker presence and smoker nonpresence. Unfortunately, most of the NHAPS study respondents were not asked to specify exactly what portion of time the smoker was present in each location. Consequently, the possibility exists for substantial overestimation or underestimation of the duration of exposure to ETS.

In Figures 3 and 4, I present three statistics from a previous analysis of the NHAPS data (*23*): the mean 24-hr cumulative duration of time spent in 10 grouped locations, the percentage of people who were in each grouped location for at least 1 min on the diary day (i.e., the doers), and the percentage of time spent in each grouped location. These statistics are reported both for all the NHAPS respondents (Figure 3) and for those people exposed to ETS at least once on the diary day (Figure 4). The statistics have been corrected with demographic, geographic, and temporal weights (*23*). The numerator of the percentage of time spent is derived from the product of the number of people present in each location that were exposed to ETS and the mean 24-hr cumulative time spent in that location. The denominator is

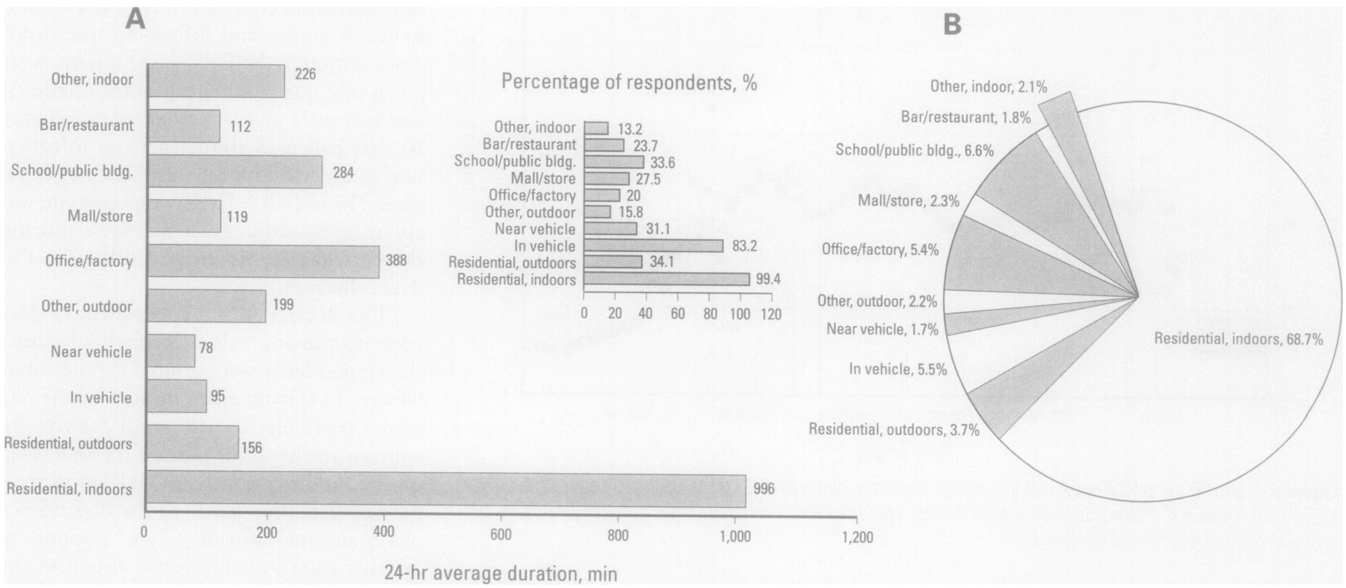

Figure 3. (*A*) The 24-hr average time NHAPS respondents spent in each location and the percentage of NHAPS respondents who reported being in each location. (*B*) The overall percentage of time spent by the NHAPS respondents in each location. Adapted from Klepeis et al. (*23*).

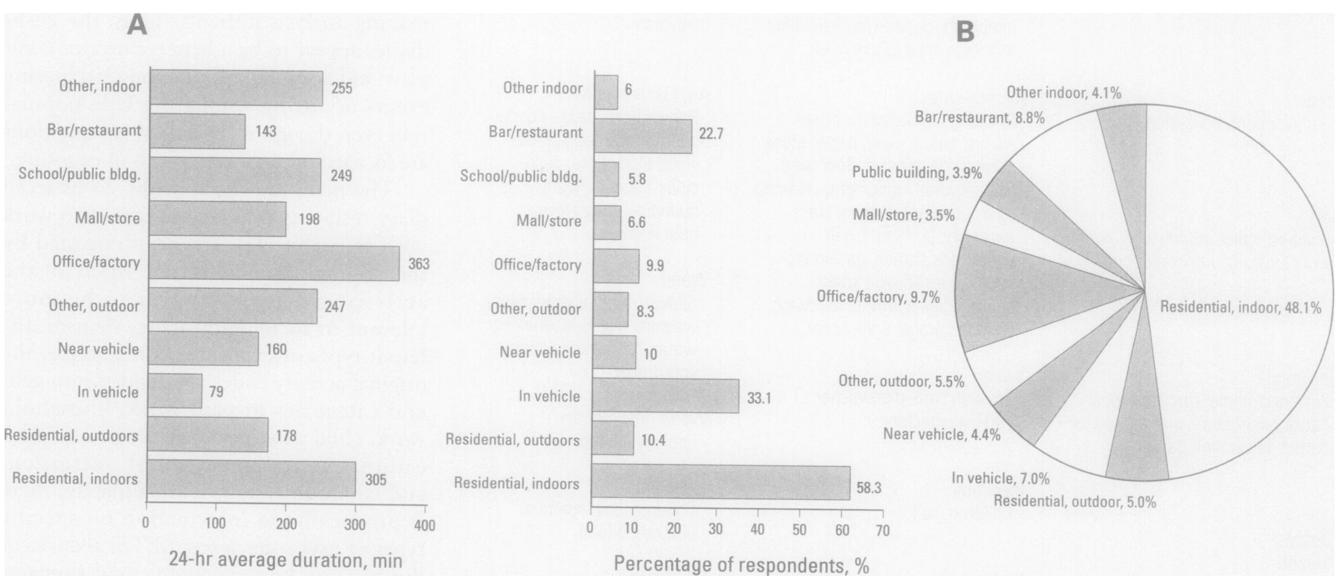

Figure 4. (*A*) The 24-hr average time NHAPS respondents spent exposed to ETS in each location and the percentage of NHAPS respondents exposed to ETS in each location. (*B*) The percentage of time spent being exposed to ETS in each location. Both *A* and *B* consider only those respondents exposed to ETS at least once on the diary day. Adapted from Klepeis et al. (*23*).

the total time spent by all respondents (total sample size × 24 hr). The 10 grouped locations we used in these analyses are: residential indoors, residential outdoors, in vehicle, near vehicle, other outdoor, office/factory, mall/store, school/public, bar/restaurant, and other indoor. Detailed descriptive statistics tables (unweighted) of many 24-hr diary categories and nearly all the follow-up questions including histograms and cumulative frequency distributions are available from Tsang and Klepeis (*24*). The analyses are broken down by 12 background variables including age, gender, race, employment status, education, and several health-related variables.

Selected Results

Of any location, Americans spend the largest amount of time in the home (69%) followed by the school (7%), a vehicle (6%), and an office or factory (5%) (Figure 3). They spend a total of 92% of the time indoors or in a vehicle. The largest mean 24-hr cumulative durations are for the home (1,000 min), the office/factory (390 min), and school or some other public building (280 min). The locations at which there were the largest percentages of people spending at least 1 min were the home (99%) and a vehicle (83%). Thus, significantly long occupational exposures in the population can be occurring for workers in an office or factory or for workers required to operate a vehicle. More people may be experiencing exposures in vehicles, but the durations of exposure are shorter than those in offices, factories, or public buildings.

ETS Exposures

In Table 3, I summarize the variables in the NHAPS database relevant to occupational as well as nonoccupational ETS exposure. Of the 9,386 total NHAPS respondents, 4,005 report having been exposed to ETS during the day. When we consider only those respondents exposed to ETS for at least 1 min on the diary day (45% of the total weighted sample size), we see that Americans are exposed for the largest amount of time in the home (48%), followed by offices or factories (10%), and bars/restaurants (9%) (*23*) (Figure 4). The longest exposures to ETS (mean 24-hr duration) occur in offices or factories (360 min) and the home (300 min). The largest percentages of people are exposed at home (60%), in a vehicle (30%), and in a bar or restaurant (23%).

Of the 4,005 people exposed to ETS, 1,619 were exposed while working their main job (*36*). The 24-hour average duration of exposure, *d*, and sample size, *n*, are given in Table 4. The table also presents the total time spent in each location by all respondents, which is obtained by multiplying *n*, by *d*.

Table 3. The 24-hr recall diary and follow-up NHAPS variables that are relevant to ETS exposure (both occupational and nonoccupational).

24-hr recall diary
Ten regrouped NHAPS locations[a]
Inside a residence
Outdoors at a residence
Inside a vehicle
Traveling outside or near a roadway or vehicle (e.g., riding a bicycle or motorcycle, walking, or waiting for the bus)
Some other outdoor location (e.g., the school grounds or a park)
Office or factory
Mall, grocery store, or other store
School, church, hospital, or other public building
Bar or restaurant
Some other indoor location (e.g., a health club, the cleaners, a beauty parlor, or a hotel/motel)
NHAPS activities
Working a main job
Traveling during work
On break during work
Working a second job
Smoker presence
Smoker present
No smoker present
Follow-up questions
Did the respondent smoke cigarettes yesterday and for how many minutes did they smoke?
Did the respondent smoke cigars or tobacco yesterday and for how many minutes did they smoke?
Did someone smoke cigarettes at the respondent's home yesterday and how many cigarettes did they smoke?
How many cigarettes did the respondent smoke outside the house yesterday?
Is smoking allowed in the respondent's home?
How many household members smoke at home?
How many total cigarettes were smoked at home?

[a]The listed locations are broad location categories created by grouping the original 83 NHAPS location codes.

Estimating Human Exposure Indirectly: Microenvironmental Concentrations Weighted by Time Spent

To estimate the total exposure of a person, we multiply measurements taken in separate microenvironments such as bars, restaurants, vehicles, homes, and offices by the time spent there as determined from responses to questionnaires such as the NHAPS 24-hr recall diary. Mathematically, we express a person's total exposure by:

$$E = \sum_{i=1}^{I} c_i t_i,$$

where E = the person's total integrated exposure, c_i = the concentration of pollutant in microenvironment i, t_i = the time spent in microenvironment i, and I = the total number of microenvironments. The person's average exposure is simply E

Table 4. 24-hr average and population minutes spent by Americans[a] exposed to ETS while working their main job (n = 1619 total).

	Residential indoor	Residential outdoor	In vehicle	Near vehicle	Other outdoor	Office/ factory	Mall/ store	Public bldg	Bar/ restaurant	Other indoor
Sample size n	91	28	73	131	64	747	144	206	135	161
24-hr average d	270	254	264	423	401	467	442	448	411	444
Total sample[b]	24,570	7,112	19,272	55,413	25,664	348,849	63,648	92,288	55,485	71,484

[a]Respondents to the U.S. EPA National Human Activity Pattern Survey. [b]The 24-hr cumulative time spent exposed to ETS for all respondents in the sample is obtained by multiplying the sample size in each location by the 24-hr average minutes spent in each location. Unpublished data from Tsang (*36*).

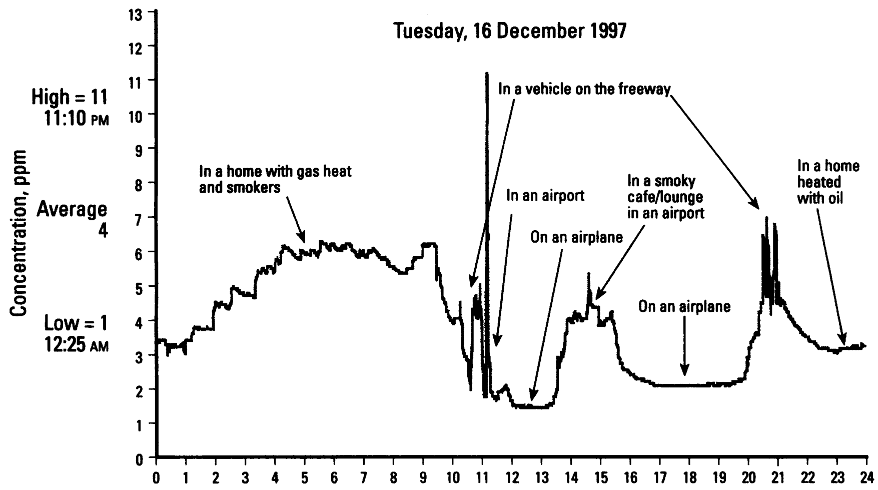

Figure 5. Plot of the author's personal CO exposure profile on 16 December 1997 as he traveled through microenvironments in a home with gas heat and smokers, in a home heated with oil, in a vehicle driving on the freeway, in an airport, in a smoky airport café/lounge, and on an airplane. This plot is a detail from Figure 1.

Table 5. Calculation of the author's 24-hr average CO exposure on Tuesday, 16 December 1997.

Microenvironment	Average concentration, ppm	Time spent, min	Concentration × time, ppm-min
At home with gas heat	5.2	631	3,281
In car on freeway	4.6	50	230
Airport	3.9	145	566
Airplane cabin	2.4	425	1,020
Home heated with oil	3.7	189	699
Total		1,440	5,796

Average 24-hr concentration = 5,796 ppm-min/1,440 min = 4.0 ppm.

Table 6. The 24-hr average RSP exposure concentration from ETS for Americans[a] working their main job.

Microenvironment (locations with a smoker present)	Average concentration, μg/m[3b]	Sample size[c]	Average time spent[d], min	Concentration × time,[e] μg/m³-min
Residential, indoors	40	91	270	982,800
Residential, outdoors	20	28	254	142,240
In vehicle	300	73	264	5,781,600
Near vehicle	30	131	423	1,662,390
Other outdoor	30	64	401	769,920
Office/factory	50	747	467	17,442,450
Bar/restaurant	60	135	411	3,329,100
Mall/store	40	144	440	2,545,920
School/public bldg	50	206	448	2,774,250
Other indoor	60	161	444	4,289,040
Total				39,719,710

Average 24-hr concentration = 41,559,860 (μg/m³)-min / (1,440 min * 1,619 people) = 18 μg/m³.

[a]Respondents to the U.S. EPA National Human Activity Pattern Survey who reported they were exposed to ETS while at their main job (activity code = 1) (Table 4). [b]The average microenvironmental concentrations are hypothetical and assumed to be the same for each person (a fairly unrealistic assumption). A more realistic calculation would multiply the time spent by each person in a given microenvironment by different exposure concentrations, which are either sampled from an empirical distribution of exposures (using the Monte Carlo method) or obtained from a deterministic model (*31*). [c]The sample size is the number of NHAPS respondents who visited each location. [d]Average time spent in each location. The product of the sample size and the 24-hr average time spent in each location across all respondents gives the total time spent by all respondents in each location (Table 4). [e]Product of the total time spent in each location (sample size time average time spent) and the hypothetical microenvironmental concentrations.

divided by the total time period of interest (e.g., 24 hr = 1,440 min). In general , we would like to have knowledge of a connected (autocorrelated) time series of microenvironments, with different microenvironments defined for different times of day, weather conditions, geographic regions, seasons, etc. Such detailed information is typically unavailable. As an approximation, we usually assume (as I do in this paper) that identical locations imply identical microenvironments.

For example, take the author's detailed CO exposure profile for Tuesday, 16 December (Figure 5; detail of Figure 1). In this case, we have available the average CO concentration in each of five microenvironments differentiated only by location (I have averaged concentrations over both contiguous and noncontiguous minutes in each location): the home with gas heating; driving in the car on the freeway; in the airport; on an airplane; and the home heated with oil. Using the equation and the average concentration and total time spent in each microenvironment (over the 24-hr period), we calculate the 24-hr average CO exposure to be 4 ppm (Table 5), which is the same concentration that is obtained by averaging over every minute in the 1,440-min (24-hr) time series.

Seldom are both detailed activity pattern information and concentration data available for a representative sample of individuals as they are for my small-scale experiment. In estimating exposures for entire populations, we consider the total time spent in a number of standardized microenvironments such as the NHAPS locations in Table 3. If we then assume that every person interviewed in the NHAPS study experiences the same ETS-derived average RSP exposure concentration while working in each microenvironment (i.e., point estimates of exposure in each location), we obtain an average 24-hr RSP exposure concentration of 18 μg/m³ (Table 6). This method does not allow determining the variability in exposure.

In a more realistic calculation, different concentrations for each person and each location would be randomly sampled from empirical distributions using the Monte-Carlo method or obtained from a mathematical model based on the mass balance equation. In this way, a more realistic frequency distribution of exposures can be determined for the given population, complete with standard deviations and percentiles of exposure. Examples of such calculations are available in published articles (*5,9*). Because models based on the indirect exposure assessment approach depend on large amounts of data for a population, very few studies have been able to conduct a complete validation procedure. When multiple and independent exposure concentration databases become available for a population, such validations should become more commonplace. For now, we rely on the accuracy of activity pattern data sets such as NHAPS and validated indoor air quality models.

Estimates of exposure using the equation are most accurate when fairly specific microenvironments are used. As a rule, the better we know exact microenvironmental exposure levels, the more accurate will be our assessment of exposure using the indirect approach. Averaging time periods of 12 to 24 hr are probably too long, as most people probably change their activities from hour to hour and high exposure levels for short time periods (e.g., 2–4 hr) are not pinpointed. Exceptions may be for sleeping and occupational settings, during which people are typically exposed in 8-hr segments. However, the occupational exposure levels are probably not constant over the work shift and individuals may spend varying amounts of time being exposed.

If multiple sources of RSP are present throughout a person's daily routine, the contributions can be added together according to a mathematical rule called the principle of superposition, which assumes that the well-mixed model assumption holds. For example, if measurements or a model show that RSP from cigarettes typically contributes, on average, 60 $\mu g/m^3$ in a restaurant and the contribution from cooking averages 10 $\mu g/m^3$, a person in a smoky bar where there is cooking would receive, on average, a total of 70 $\mu g/m^3$ of RSP exposure. Exposure from other sources of RSP besides ETS—vehicle emissions, wood burning, or cooking—could also be included and the contribution of each source to the total exposure examined.

Population exposures can be recalculated for any hypothetical microenvironmental concentrations to explore the effects of different control strategies. For example, suppose occupational exposures to ETS in vehicles were drastically reduced by a smoking ban. What would happen to the national average exposure? For the example given above, the average RSP exposure would decrease from 17 to 15$\mu g/m^3$. Thus, we predict that ETS exposure in vehicles contributes, on average, 2 $\mu g/m^3$ to the overall U.S. occupational exposure.

Conclusions and Future Work

In this paper, I have illustrated the indirect approach to exposure assessment by showing how the average 24-hr exposure concentration determined from an actual minute-by-minute exposure profile can be approximated by summing the product of two separate components: average microenvironmental concentrations obtained from models or measurements, and the time spent in each microenvironment. Once these components are representatively determined for a population, a realistic frequency distribution of exposures can be calculated for the status quo and almost any hypothetical exposure control scenario. It is possible to examine fractions of a 24-hr period and individual locations and pollutant sources. The existence of representative surveys of exposure to ETS components in many microenvironments, validated ETS models for microenvironments such as the car, the tavern, and the smoking lounge, and a nationally representative survey of human activity patterns should compel exposure assessors to make use of this powerful and inexpensive approach.

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